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CRYOGENIC REACTANT STORAGE FOR SPACE ELECTRICAL POWER SYSTEMS

A large portion of electrical power systems currently under development for spacecraft applications will require chemical energy sources in the form of expendable reactants, usually hydrogen and oxygen. These reactants are most efficiently stored, from a weight and volume standpoint, in the liquefied state. Since many of these reactants boil at low temperatures, refrigeration is frequently required for their liquefaction and storage.

The science of refrigeration by mechanical means began a little over a century ago with the development of the first refrigeration machine. Since then, much effort has been directed toward obtaining progressively lower temperatures. This effort has led to the science now known as cryogenics, which deals with the engineering processes of fluids at temperatures approximately below -140°F. Four of the more familiar cryogens and their boiling temperatures at one atmosphere of pressure are: oxygen, -297°F; nitrogen, -320°F; hydrogen, -423°F; [illegible] -452°F. The science of refrigeration at cryogenic temp[illegible] progressed to the point where it is now possible to approxim[illegible], for [illegible] practical purposes, the minimum physically possible temperature of 0°K (-4[illegible]°F).

One of the early airborne applications for cryogenics was in the German V-2 rocket program. More recent applications have been in the research and development of propulsion systems using cryogenic propellants, liquid oxygen systems for aircraft environmental sys[illegible], and liq[illegible] nitrogen for infrared detection systems. The X-15 airplane, which has recently [illegible]netrated the fringes of space, uses a liquid nitrogen system for cooling [illegible] well as for pressurizing the cabin and equipment bay. While this system

ABSTRACT

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The advent of manned space missions has resulted in the present importance of cryogenic storage and delivery systems capable of operating for extended periods in zero gravity. This discussion deals with current methods of cryogenic storage to satisfy the requirements of spacecraft electrical power system reactant and environmental supplies. Supercritical and subcritical cryogenic storage systems are discussed. Supercritical storage is presently being developed for existing manned space flight programs; therefore, most of this discussion is devoted to considerations of this type storage system.

is exposed to weightlessness for short periods, it is not designed for long term use in weightless environment. With the advent of manned space missions, requirements have resulted for development of cryogenic storage systems capable of operating in zero gravity for extended periods of time.

The discussion presented herein deals with cryogenic reactant storage to satisfy the requirements of space electrical-power-generation systems for extended manned spacecraft missions. Supercritical cryogenic storage is currently the most important method of supplying cryogenic reactants in space programs; therefore, most of the remaining portion of this paper is devoted to applicable thermodynamic considerations of supercritical cryogenic storage.

Electrical power for America's next generation spacecraft, Gemini and Apollo, will be supplied by fuel cell systems requiring hydrogen and oxygen as reactants. To satisfy the fuel cell and metabolic requirements on Apollo, approximately 640 pounds of oxygen and 56 pounds of hydrogen, cryogenically stored, will be required. The importance of using cryogenic storage to satisfy these requirements may be shown by comparing relative system weights.

The relative weight of three candidate storage systems is illustrated in Figures 1 and 2 for hydrogen and oxygen, respectively.

Figure 1

Figure 2

The high pressure gaseous storage system represented by curve "A" of Figure 2 is currently used in the Mercury Spacecraft 7,500 psia gaseous oxygen supply. Examination of curve "A" in Figures 1 and 2 reveals that the weight penalty associated with the high-pressure gaseous storage system limits its usefulness to missions with very low fluid consumption requirements. Supercritical cryogenic storage, represented by curve "B", is similar to high pressure gaseous storage in that the fluid always exists in the single phase state, with the operating pressure above the critical pressure. However, the supercritical system permits large payload quantity storage with much less volume and storage system weight. A subcritical cryogenic system with normal storage pressure maintained below the fluid critical pressure is represented by "C". Quantity measurement and flow control problems are currently associated with the utilization of two-phase liquid-vapor subcritical systems in a zero gravity environment.

Supercritical cryogenic storage assures single phase fluid storage under all gravity conditions. The fluid mostly resembles a liquid or a vapor, depending upon its temperature; since the pressure is maintained above the fluid critical pressure, there is no liquid-vapor interface. Due to its inherent simplicity, the supercritical method of storage is the current choice for cryogenic reactant supply systems. This type of system is presently being developed for the Gemini as well as for the Apollo spacecraft. The characteristics of supercritical system operation are indicated on the pressure-enthalpy and temperature-entropy diagrams of Figure 3.

Figure 3

Point 1 indicates the initial fill condition where cryogenic liquid is charged into the system until the desired fill capacity is achieved. After fill is completed, a mixture of saturated liquid and saturated vapor at fill pressure will occupy the storage vessel. Pressurization from point 1 to operating pressure at point 3 is accomplished by normal heat leakage to the fluid during standby or may be supplemented with internal heaters. During pressurization from point 1 to point 2, the liquid density will decrease until the total volume of the vessel is occupied by saturated liquid at point 2.

Neglecting vessel expansion, the liquid is further heated which results in pressure and temperature rise to point 3 with no change in density.

The required heat input for complete pressurization may be determined by the following relation, reference 1:

$$Q_{A_{1-3}} = W(h_3-h_1) - \frac{144W}{J\rho}(p_3-p_1)$$

Where: W = loaded fluid weight, pounds

J = energy equivalent of heat (778 ft-lb per Btu)

h = fluid specific enthalpy, Btu per pound

p = pressure, psia

ρ = fluid density, lb per ft^3

$Q_{A_{1-3}}$ = heat added, Btu, between points 1 and 3

Upon reaching the system operating pressure indicated by point 3, fluid withdrawal may begin. As fluid is withdrawn from the system, the addition of heat is required to maintain operating pressure above the fluid critical pressure and assure continuation of single phase fluid storage throughout the mission. As the fluid state reaches the superheated vapor condition indicated by point 4, heat input requirements to maintain constant pressure become excessive and the pressure is allowed to decay. Ambient heat leakage into the vessel is normally adequate to maintain a somewhat isothermal pressure decay along the path 4-5, with the fluid maintained in the superheated condition.

The heat input requirements for constant pressure supercritical operation may be determined by the following relationship given in reference 2.

$$Q_A = \rho\left(\frac{dh}{d\rho}\right)$$

Where: Q_A = heat input per unit fluid weight expelled, Btu per lb

ρ = fluid density, lb per ft^3

h = specific enthalpy, Btu per lb

Figures 4 and 5 indicate the heat input requirements as a function of fluid quantity remaining for hydrogen and oxygen, respectively, at various operating pressures.

Figure 4 Figure 5

The maximum heat input requirements for constant pressure operation occur as fluid quantity depletion nears. Therefore, to prevent excessive power requirements, the pressure is allowed to decay after the temperature is sufficiently higher than the critical temperature.

In order for the system to perform efficiently, the maximum ambient heat leakage to the fluid through insulation, supports, and tubing in a nonventing system should not be greater than the minimum heat input indicated by the bottom of the curves in Figures 4 and 5. This minimum point usually determines the maximum design heat leakage for the system. However, if extended nonventing standby time is required, the allowable standby heat leakage may be less than the operational minimum; for such cases, the standby heat leakage will establish the insulation requirements.

While the supercritical cryogenic storage method ensures single-phase fluid storage, it provides single-phase fluid delivery only with proper fluid heating prior to expansion to lower useable pressure. With proper heating of the withdrawn fluid, the supercritical storage method prevents two-phase flow, and pressure fluctuations associated with the flashing of liquid to vapor in supply line superheaters do not exist.

Due to the lack of convective currents in a zero gravity environment, severe temperature and density stratification may occur in supercritically stored cryogenic fluids. At present, capacitance probes are being developed for the Apollo and Gemini systems which will indicate the stored reactant quantity as a function of its density. At constant pressure, the density is dependent upon temperature, and the presence of mild temperature stratification could result in extremely erroneous fluid quantity gauging.

Figures 6 and 7 show the variation of fluid density as a function of temperature for hydrogen at 250 psia and oxygen at 1,000 psia, respectively.

Figure 6 Figure 7

It may be noted from these curves that very slight temperature stratification can result in considerable error in quantity gauging. Methods for fluid mixing and conductive heat transfer paths to prevent stratification are being investigated.

One of the more difficult problems currently associated with supercritical storage and which is also attributed to the lack of convective currents, is that of heat transfer to the stored fluid. A solution to this problem would probably eliminate the problem of temperature stratification. One solution is to utilize perforated concentric spherical heat exchangers within the stored fluid to provide maximum heat transfer area with minimum weight penalty.

The method of using high heat transfer area is inherently simple and contains no moving parts within the fluid. However, it does add undesired weight to the system. An alternate approach is to establish circulation within the stored fluid. This will provide convective currents for better heat transfer and break up stratification within the fluid. There are several means of initiating circulation within the fluid. Perhaps the most common is the use of a motor driven paddle wheel or propeller.

The subcritical cryogenic storage system offers significant tankage weight advantages over supercritical systems due to lower operating pressures. At present there are several concepts for subcritical cryogenic storage, none of which has been developed for use in zero gravity conditions. One of the most promising is the thermally regenerative, two-phase system.

In this system, the fluid is pressurized and operating pressure is maintained with the addition of heat to the fluid. Since the normal operating pressure is maintained below the fluid critical pressure, the fluid exists in both the liquid and vapor phase. Figure 8 shows subcritical two-phase operation on pressure-enthalpy and temperature-entropy diagrams.

Figure 8

Liquid is charged into the system at point 1 until the desired fill is achieved. Pressure buildup from point 1 to 2 may be accomplished thermally with the addition of heat or with hydrostatic fill pressure. Upon reaching the desired operating pressure, fluid withdrawal may begin. As fluid is withdrawn, the average density of the remaining fluid, which is maintained at constant pressure and constant temperature, is decreased through the two-phase region until all of the liquid is either expelled or vaporized as illustrated by point 3 on the saturated vapor line. Further fluid withdrawal, with heat addition to maintain constant pressure, superheats the fluid to the condition indicated by state 3. If the operating pressure is sufficiently higher than the required delivery pressure, it may be allowed to decay to the condition indicated by state 4.

In the absence of a gravitational field, the location of liquid is difficult to predict and quantity measuring problems are encountered. The matrix-capacitance-gauging method works in two-phase mixtures. In this method of fluid measurement the fluid acts as electrolyte and the quantity is measured as a function of the capacitive reactance. Since the matrix occupies the complete vessel volume, it indicates the amount of remaining fluid regardless of fluid phases or density stratification within the fluid.

However, the weight penalty associated with this method will prohibit its use in the larger systems. One possible solution to the quantity measuring problem is to use an integrating flow measuring system to indicate the stored quantity as a function of the quantity withdrawn.

Single phase vapor delivery can be assured with the subcritical system by the addition of heat to the fluid before expanding to lower pressures; however, for high flow rates, the alternate withdrawal of liquid and vapor from storage usually leads to flow regulation problems. As the cryogenic liquid comes into contact with warm superheaters, it flashes into vapor and the maximum pressure surges to the saturation pressure at maximum fluid temperature. For extremely low flow rates, and rather long supply lines, this may present a minor problem.

Another concept for two-phase subcritical storage in zero gravity is that of using the vapor-liquid-solid intermolecular forces to facilitate ullage control. These forces, which appear in the form of surface tension forces, are the only forces acting on a liquid in a complete zero gravity environment. The underlying principle in this concept is that the liquid-vapor interface will seek a configuration to satisfy any unbalanced forces. When the liquid reaches its equilibrium configuration, it is said to have reached its position of minimum energy due to the fact that all pressures, interface surface areas, and unit surface energies are in balance. This concept has been verified experimentally by personnel at Lewis Research Center, Reference 3.

An experimental tank equipped with a standpipe to demonstrate ullage control was placed aboard the Mercury spacecraft which was launched May 24, 1962. The system performed as predicted and demonstrated that relatively small accelerations could be sustained without forcing the liquid from the standpipe. Figure 9 shows a sketch of the tank with its zero gravity liquid-vapor interface configuration.

Figure 9

The capacity of the vessel shown was 300 milliliters; the fluid was water mixed with a mild detergent to decrease its surface tension.

With a thorough knowledge of the equilibrium liquid-vapor interface configurations in various tank geometries, it is currently believed that subcritical cryogenic systems could be designed to solve the problems associated with venting and liquid orientation in two-phase systems.

At the present time there is no reliable method for expelling cryogenic liquids under zero gravity conditions. Various positive expulsion concepts for cryogenic fluids have been investigated. Several basic types of positive expulsion systems have been considered; the most common are bladders, bellows, diaphrams, and pistons. Of these basic types, bladder systems have the highest expulsion efficiency and the lowest weight; therefore, considerable attention has been directed toward their development. The term "bladder", as used relative to positive expulsion systems, denotes a pliable film with tailored shape to fit the inside of the liquid container. The bladder is inflated or collapsed, as desired, by external gas pressure, to force the liquid from the vessel. Bladder systems are currently in use for storable propellant applications where extreme temperature conditions are not experienced. A suitable bladder material has not yet been found that will withstand flexing and folding while being subjected to temperatures as low as that of liquid hydrogen at $-423^{\circ}F$. There has been little or no effort directed toward developing bladders for fluids with temperatures above that of hydrogen. Since the problem is essentially due to temperature, any material that will work with hydrogen should work with warmer cryogens. If a suitable bladder material could be found, it would be possible to design satisfactory subcritical positive expulsion systems for cryogenic liquids.

Récent developments in insulating materials and techniques have significantly contributed to the efficient application of cryogenic systems in space. The insulations used for current cryogenic storage applications are almost exclusively of the superinsulation class. Superinsulations consist of alternate layers of a highly reflective material, such as aluminum and poor conductive material such as fiberglas paper. The insulation, which may have up to 150 layers per inch of thickness, must be evacuated to a pressure of about 10^{-5} torr in order to attain optimum insulating efficiency.

The main problem associated with the superinsulations is that of application to various vessel geometries. Installation requires special techniques to prevent loading from the vessel walls and minimization of lateral heat leakage to supports and fluid transfer lines.

In closing, it is noted that at the present time supercritical storage offers the most simplicity in operation with inherent reliability and availability of system components. This method offers significant weight savings over the high pressure gas storage method and provides single phase storage. Like subcritical storage, it provides good volumetric efficiency. However, since further weight savings are possible in the low pressure subcritical systems, techniques must be developed to facilitate use of subcritical systems in zero gravity.

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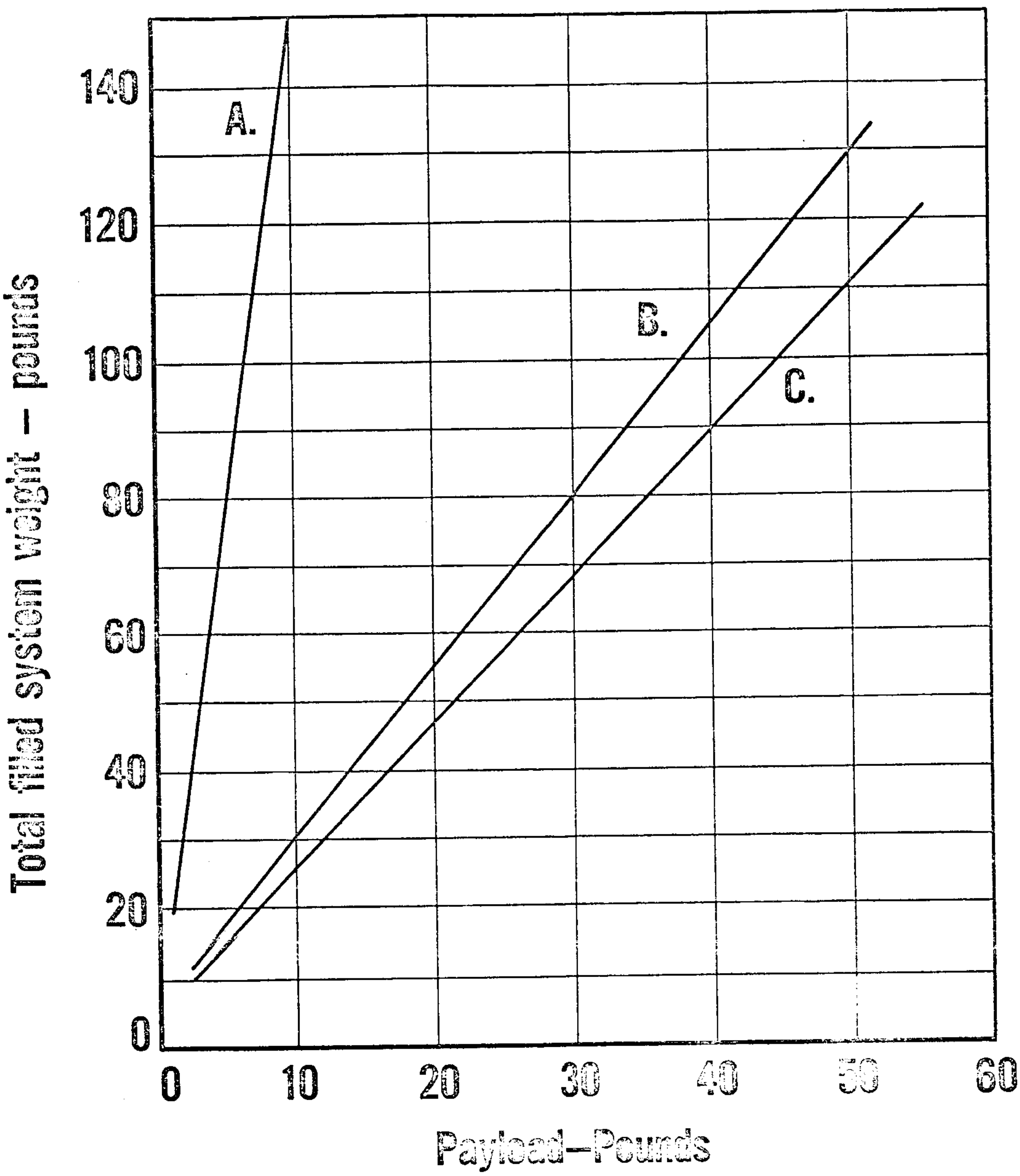
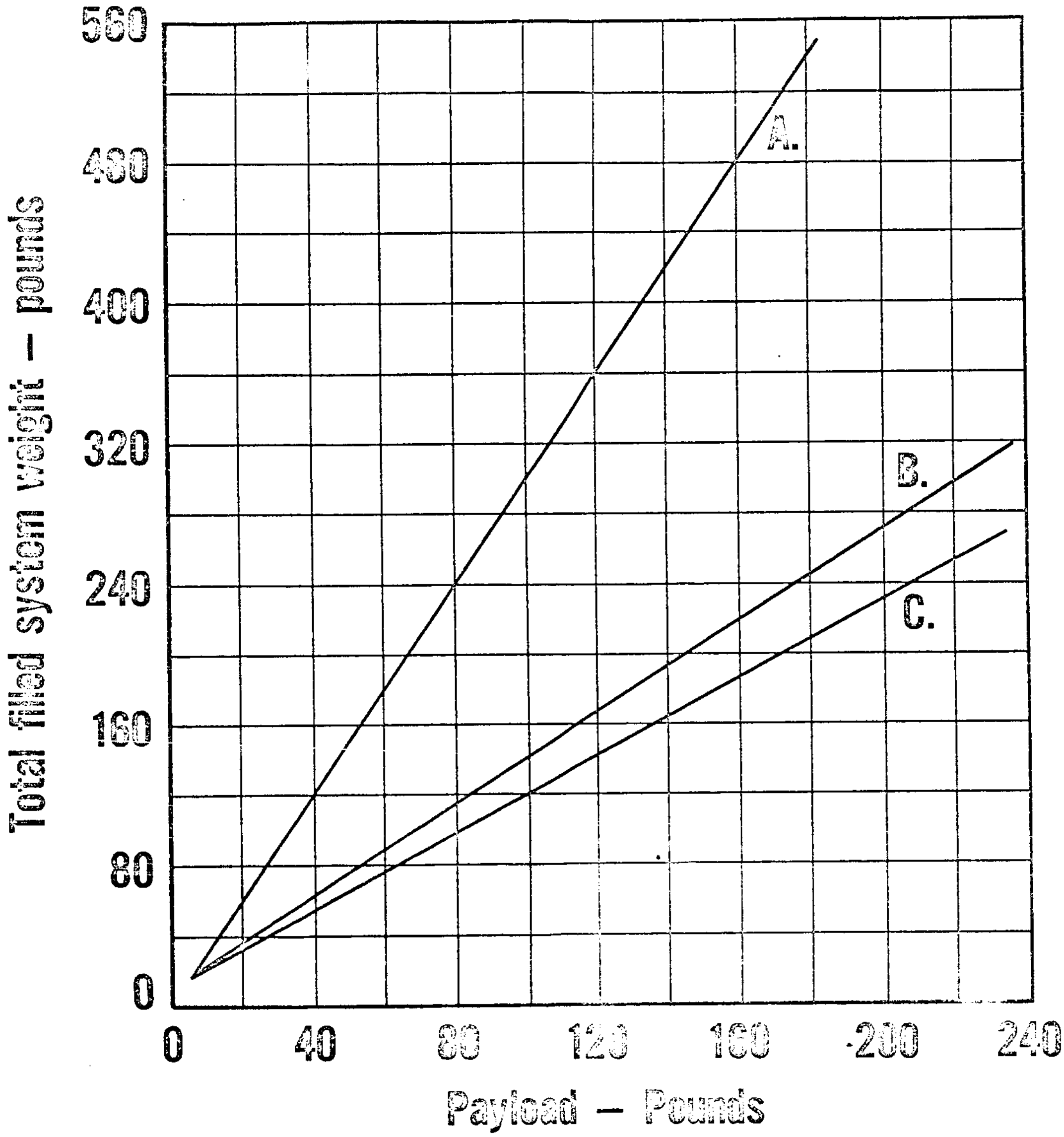


A. High pressure gaseous storage, 1000 psia

B. Supercritical cryogenic storage, 300 psia

C. Subcritical cryogenic storage, 50 psia

Figure 1. Total hydrogen tankage weight as a function of fluid payload



A. High pressure gas storage, 7500 psia

B. Supercritical cryogenic storage, 850 psia

C. Subcritical cryogenic storage, 150 psia

Figure 2. Total oxygen tankage weight as a function of fluid payload

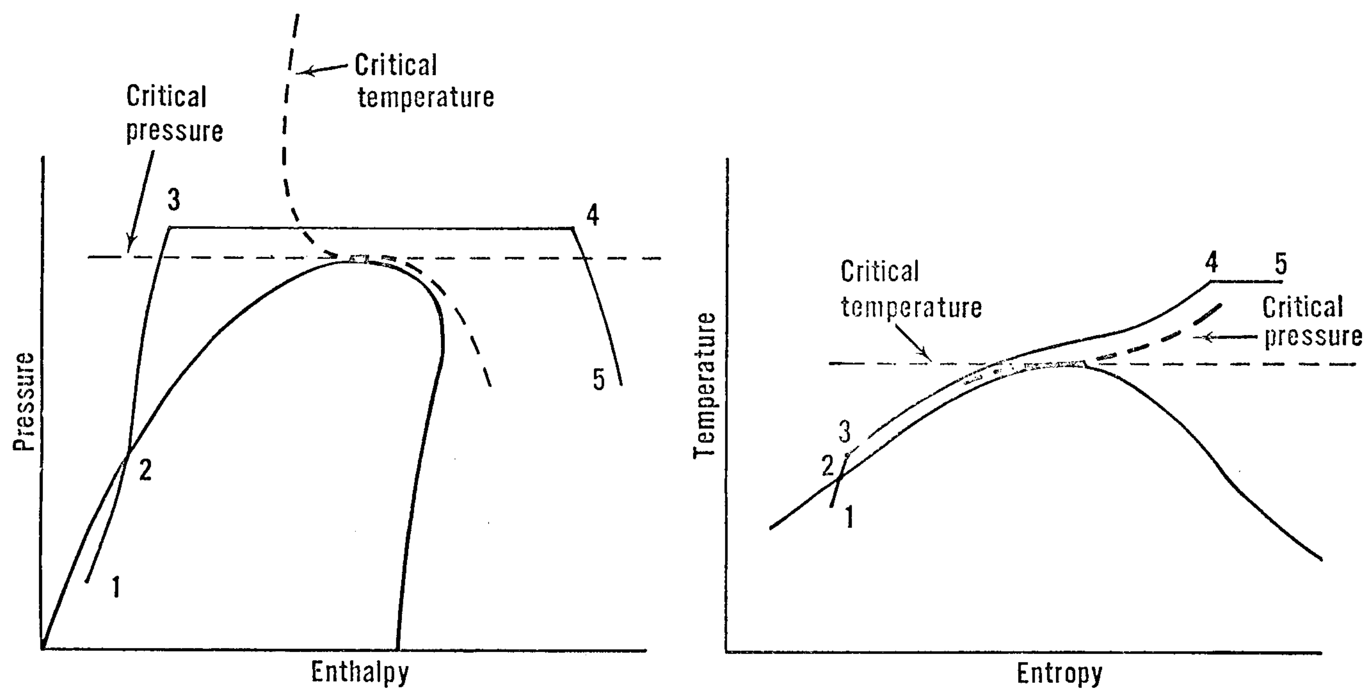


Figure 3. Supercritical operation on pressure-enthalpy and temperature-entropy diagrams.

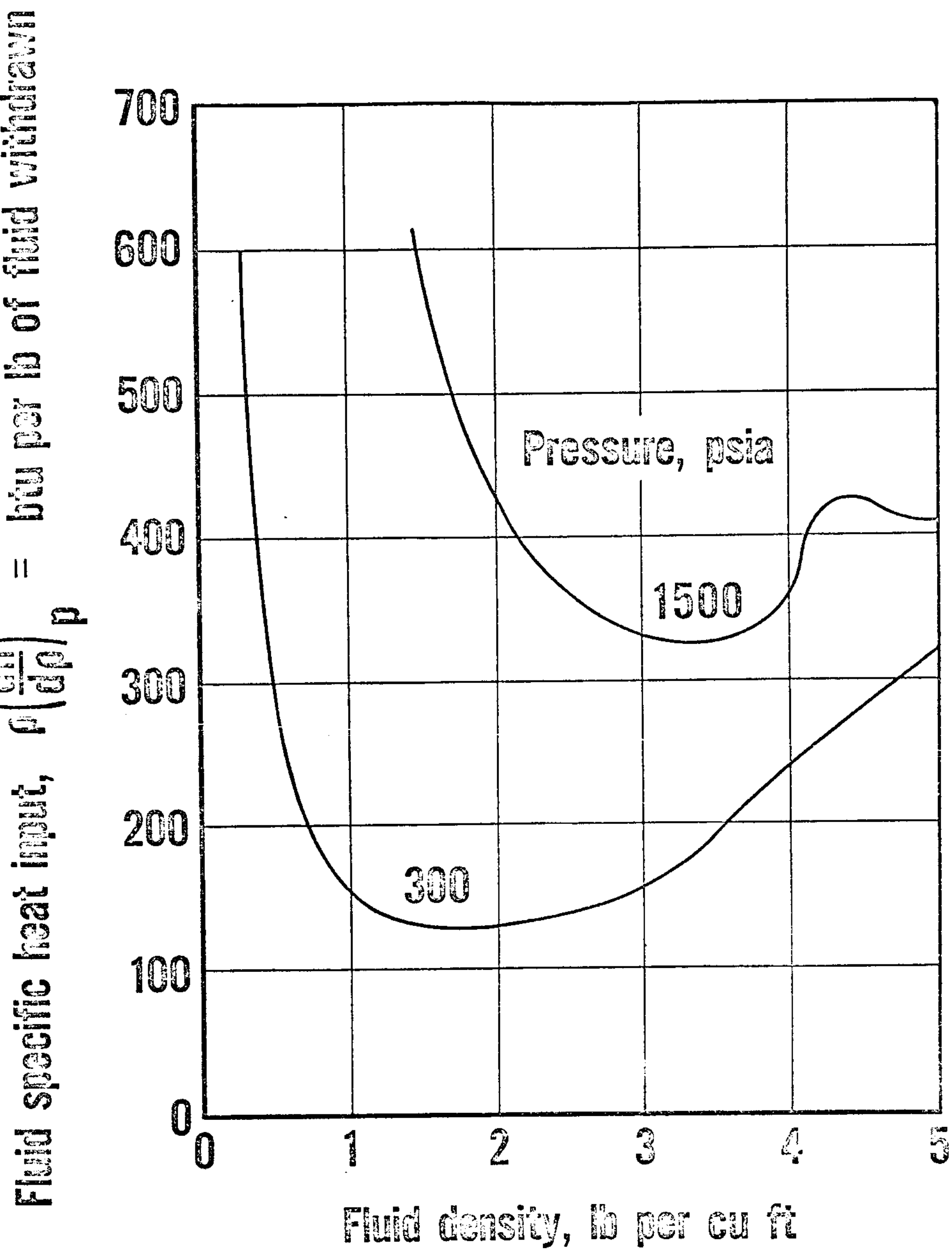


Figure 4. Specific heat input for constant pressure delivery, supercritical hydrogen storage

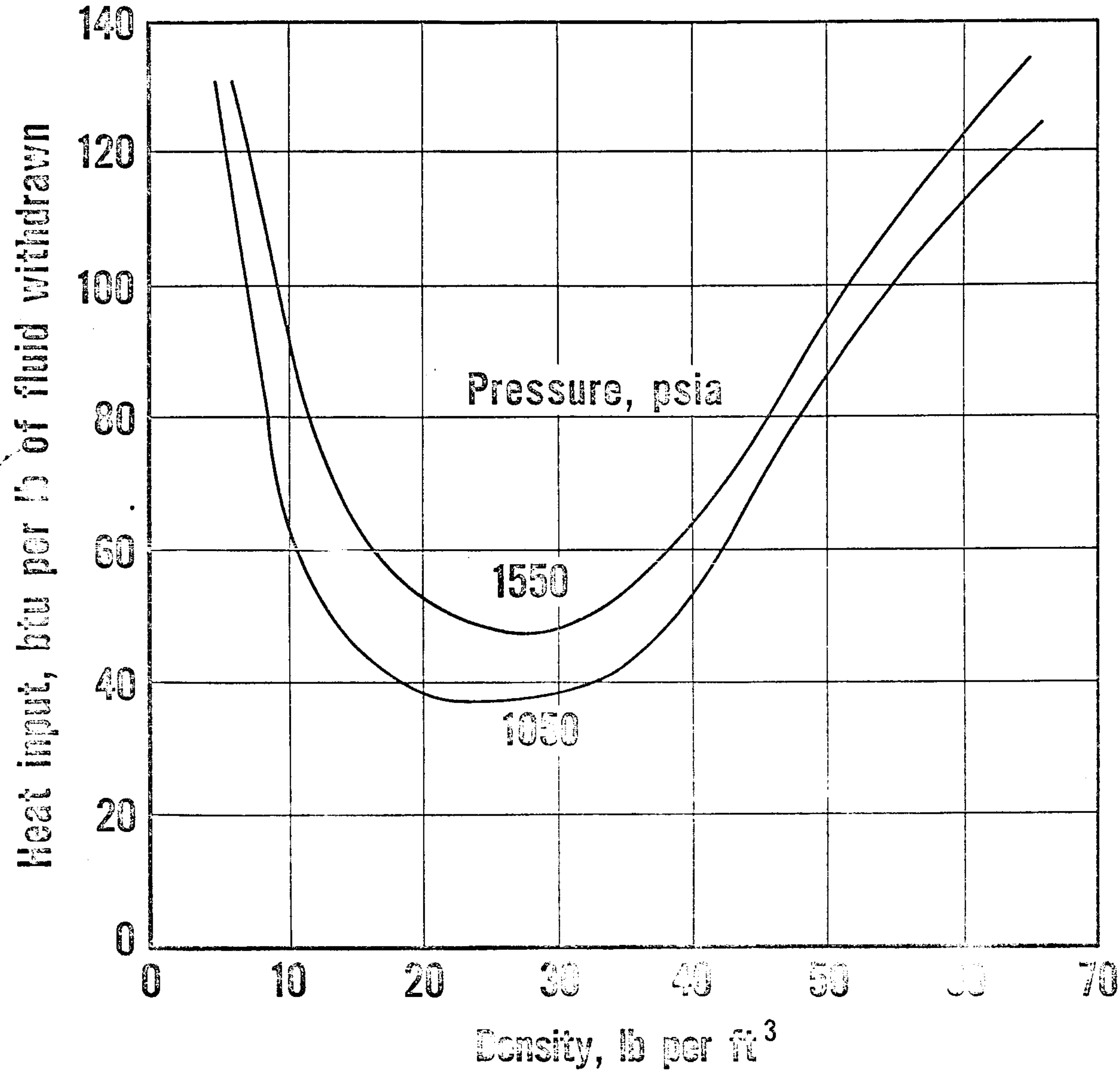


Figure 5. Specific heat input for constant pressure delivery, supercritical oxygen storage

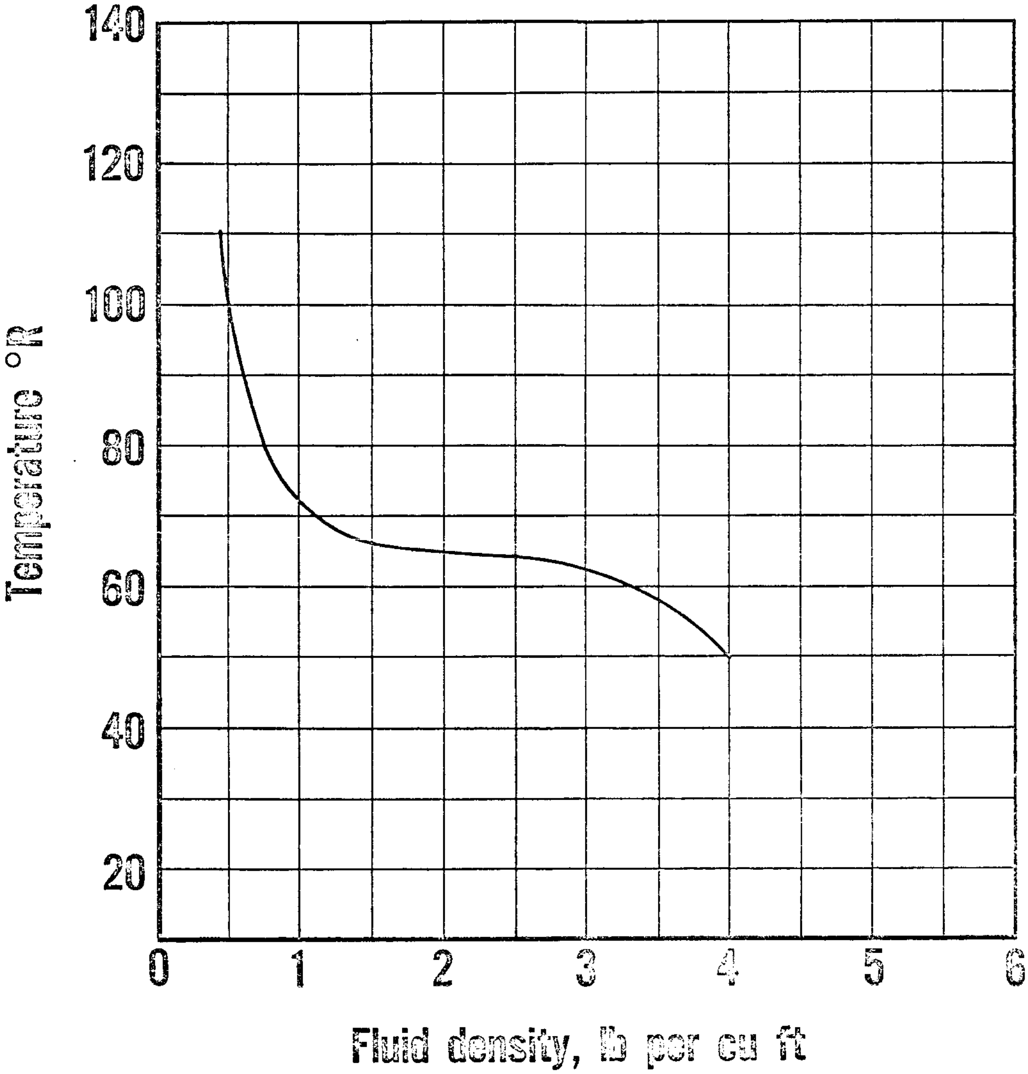


Figure 6. Temperature vs density for supercritical hydrogen, 250 psia.

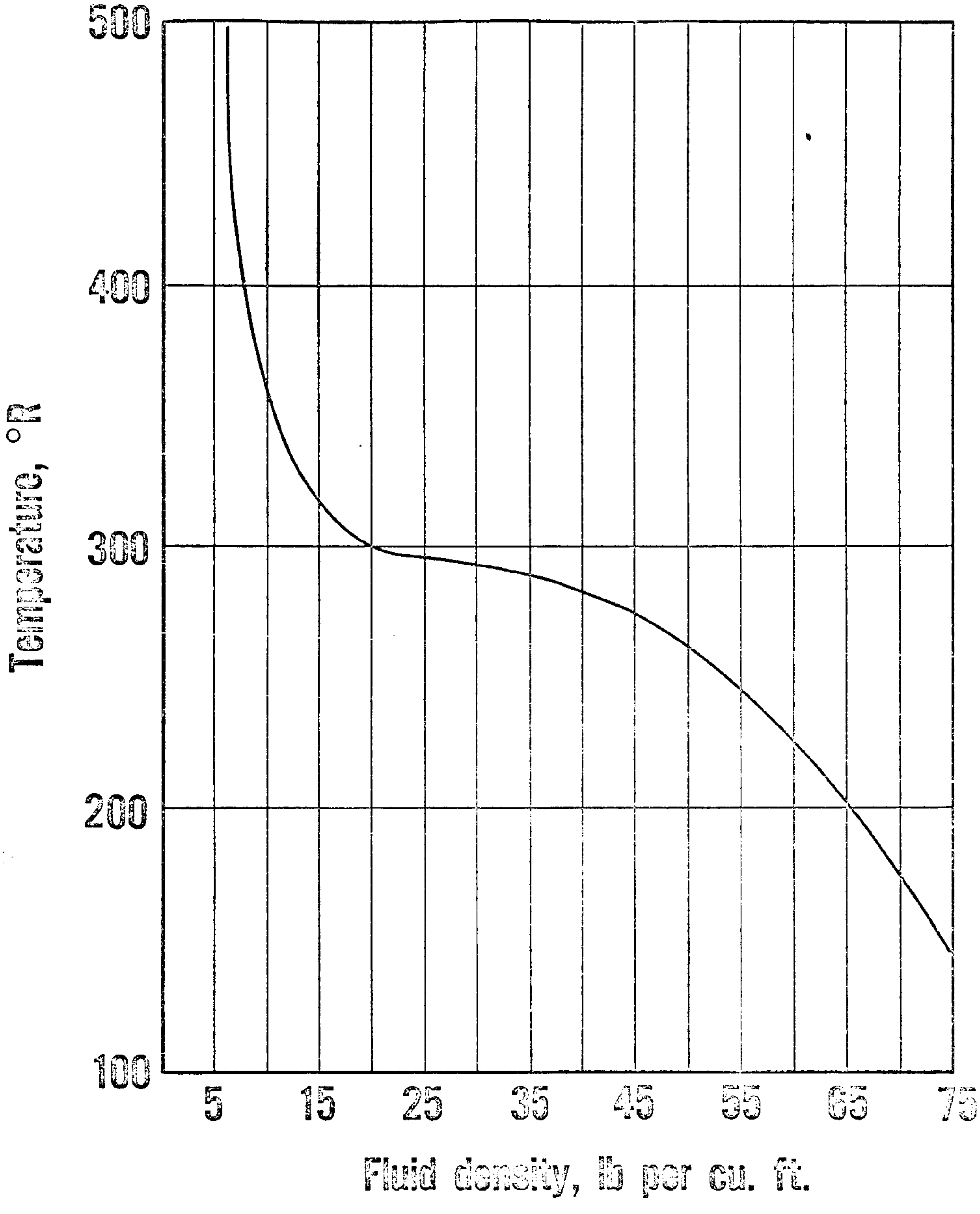


Figure 7. Temperature vs density for supercritical oxygen, 1000 psia

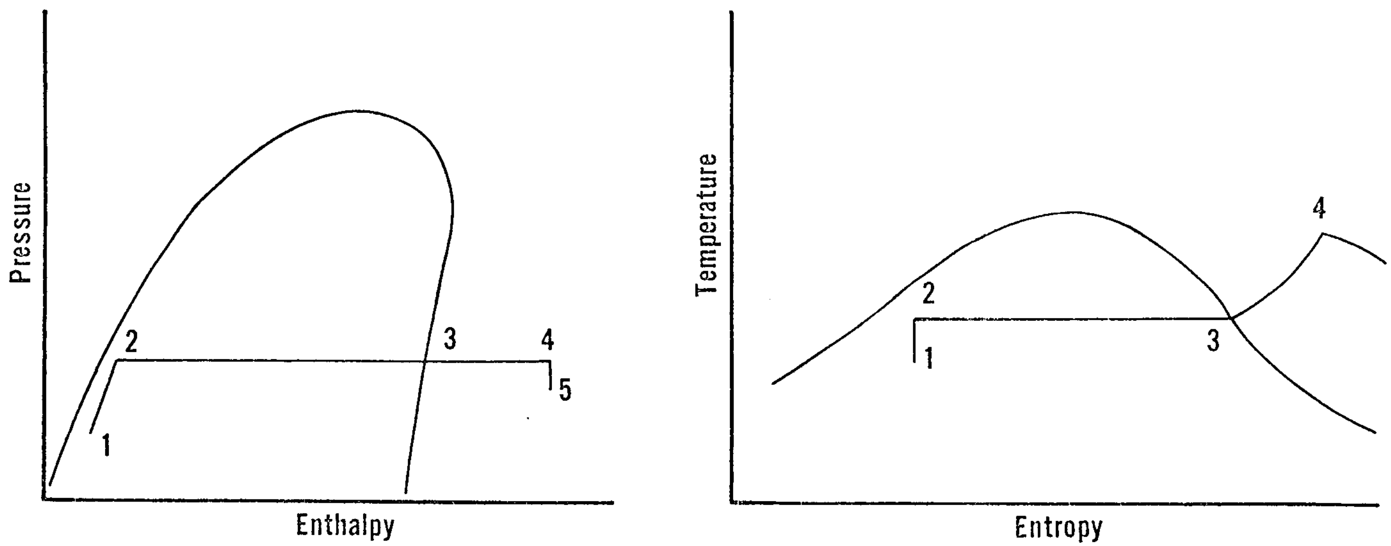


Figure 8. Subcritical operation on pressure-enthalpy and temperature-entropy diagrams.

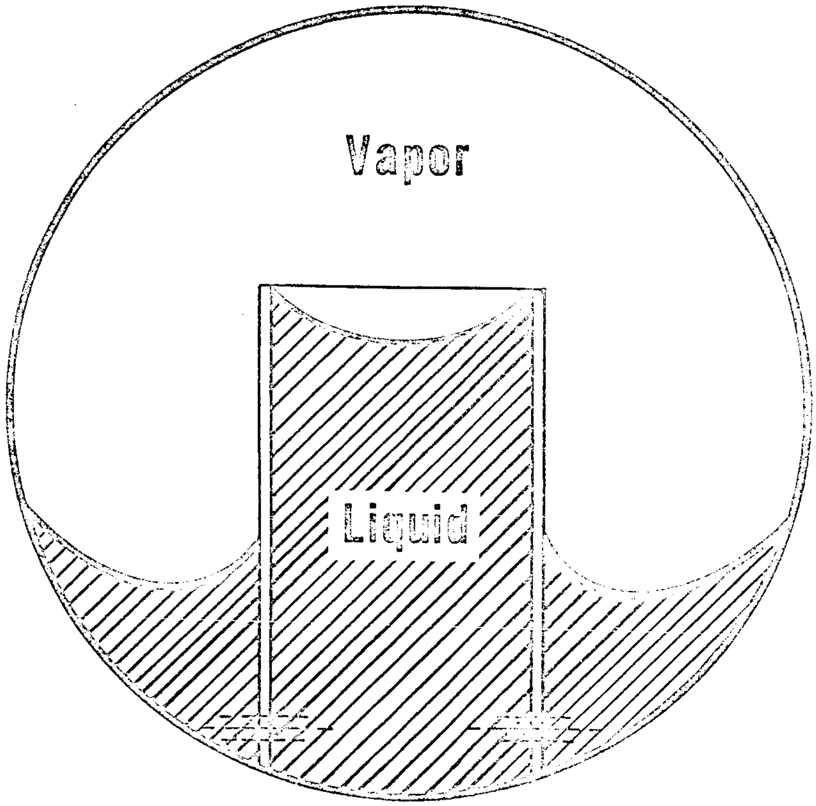


Figure 9. Typical zero gravity equilibruim configuration of wetting liquid in spherical vessel with standpipe.